Radboud University

university of groningen

ASTRON

Netherlands Institute for Radio Astronomy

Study of the cosmic ray radio emission pattern at ground level with LOFAR

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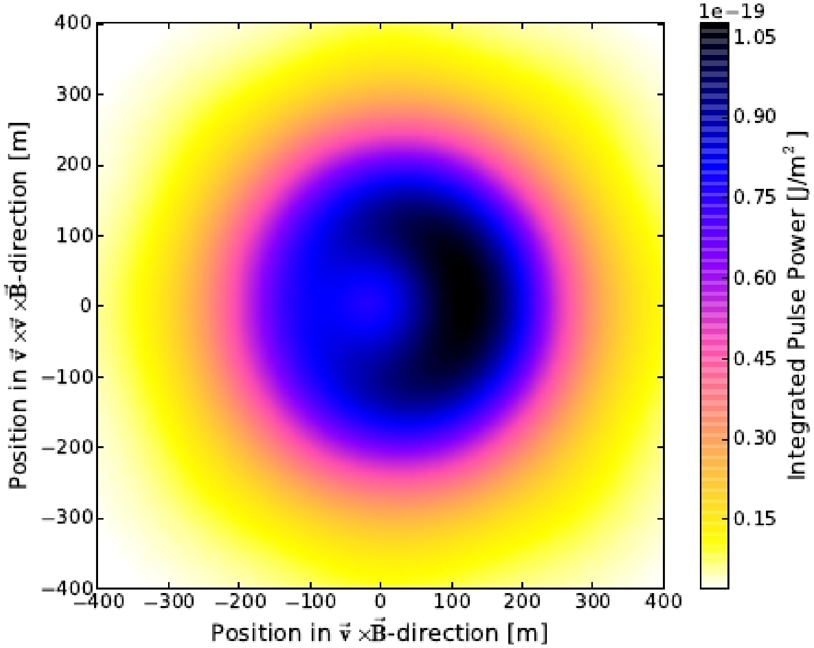
on behalf of the Cosmic Ray Key Science Project

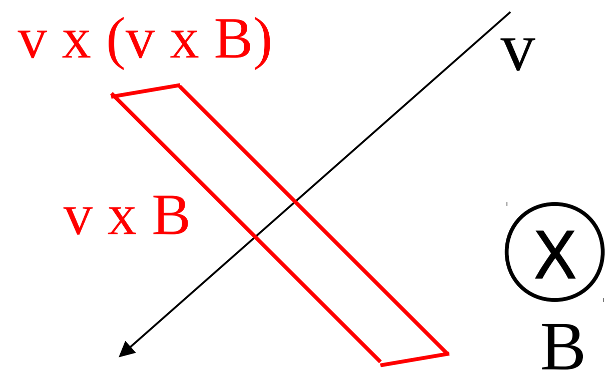
LOFAR Science Workshop, Assen, June 2nd – 3rd 2015

The footprint of the radio signal

A. Nelles et al., 2014, Astroparticle Physics, 60, 13-24

A. Nelles et al., 2015, Journal of Cosmology and Astroparticle Physics 05, 018



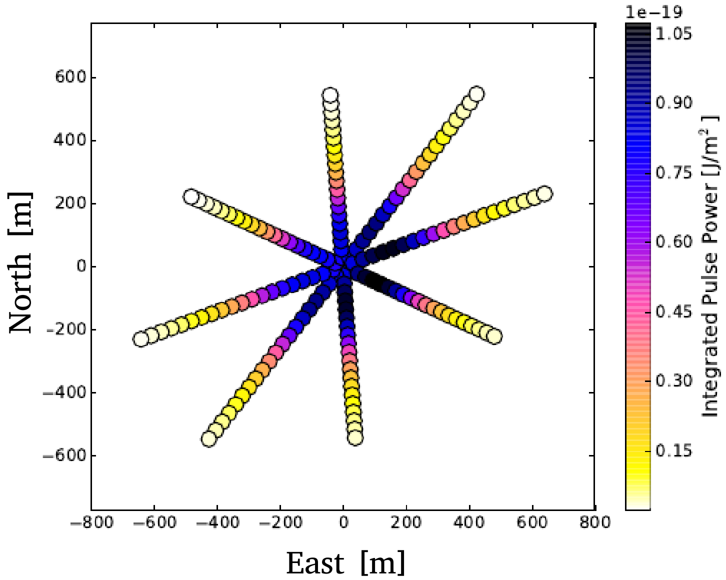


v = shower axis

B = Earth magnetic field vector

What is the shape of the radio signal footprint?

Simulation study



On the ground level

Particle production

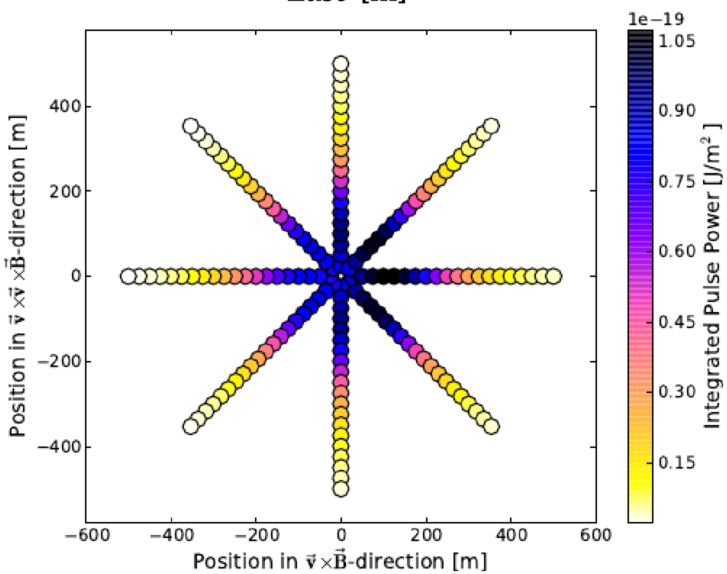
→ CORSIKA 7.400

with FLUKA 2011.2b and QGSJETII.04

Radio emission → CoREAS

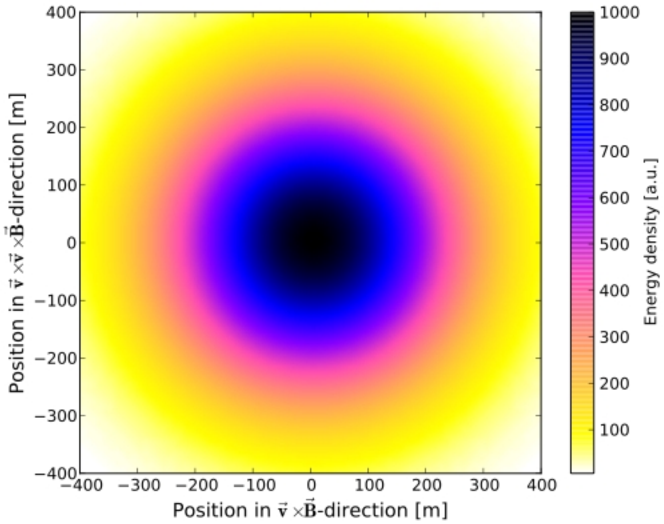
Energy = 10^{16} – $10^{18.8}$ eV, zenith = 3° – 55°

Antenna layout → star–shape pattern in the shower plane



Plane perpendicular to the shower axis

Simulation study

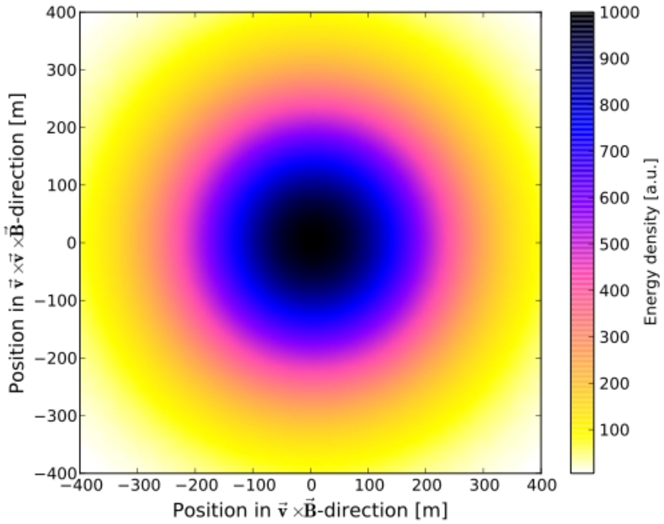


Two-dimensional Gaussian distribution

$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right)$$

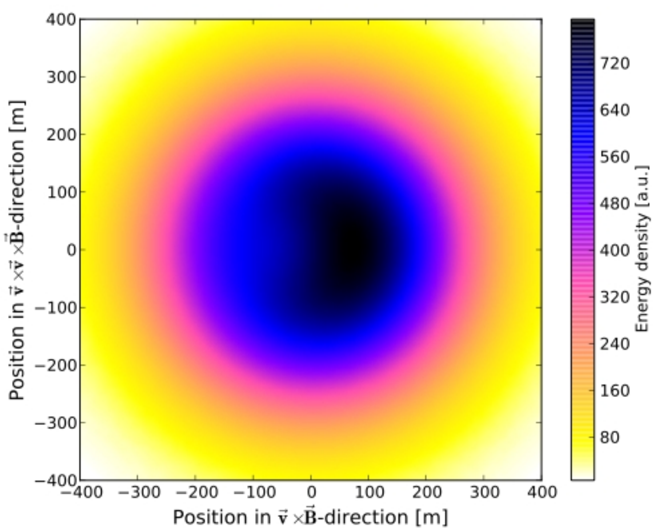
P → total power of the integrated signal
x' → coordinate along the v x B direction
y' → coordinate along the v x (v x B) direction
X_+ → location parameter along v x B
Y_+ → location parameter along v x (v x B)
σ_+ → width parameter
A_+ → amplitude parameter

Simulation study



Two-dimensional Gaussian distribution

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right)$$



“Bean shape” → combination of two-dimensional Gaussian distributions

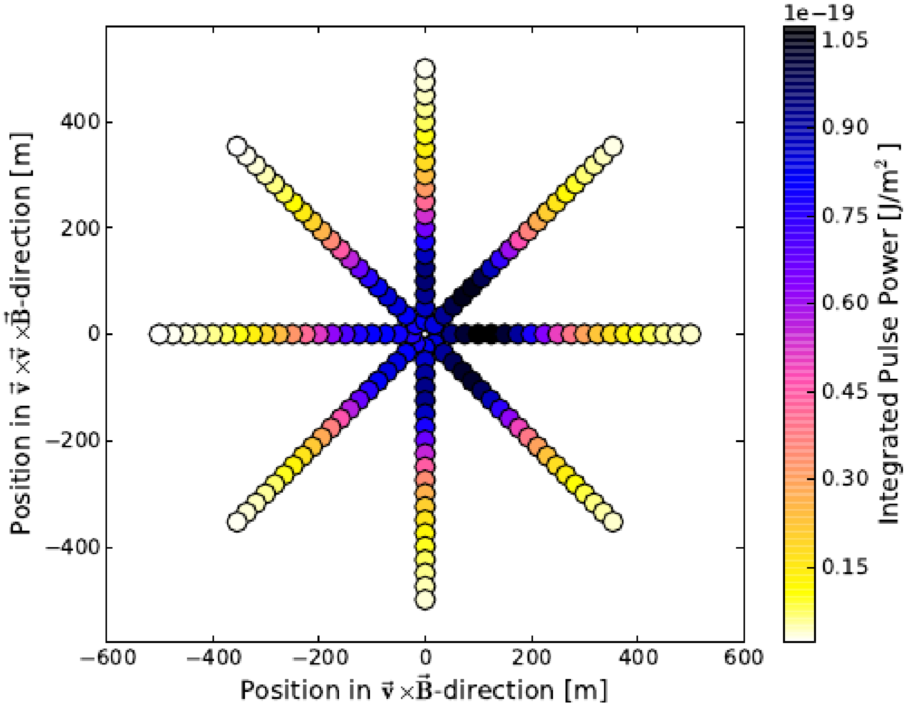
$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right) + O$$

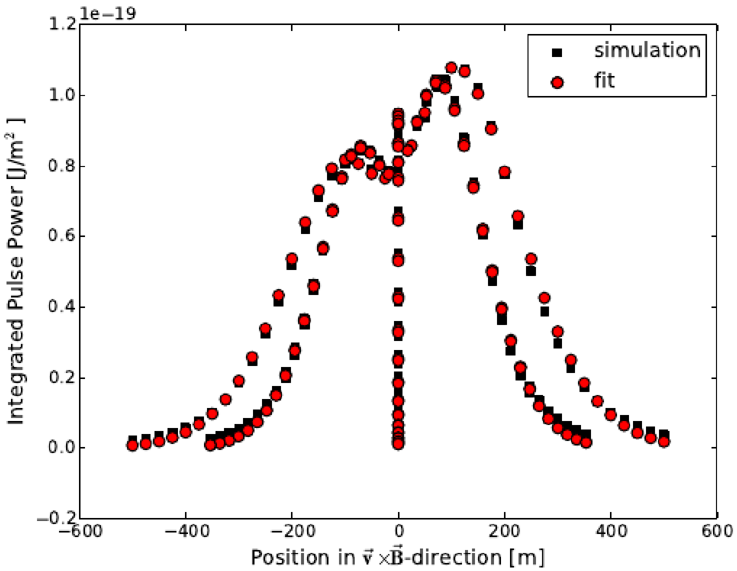
→ The two Gaussians are shifted and subtracted from each others ($A_+ > A_-$)

→ 9 free parameters

Simulation study

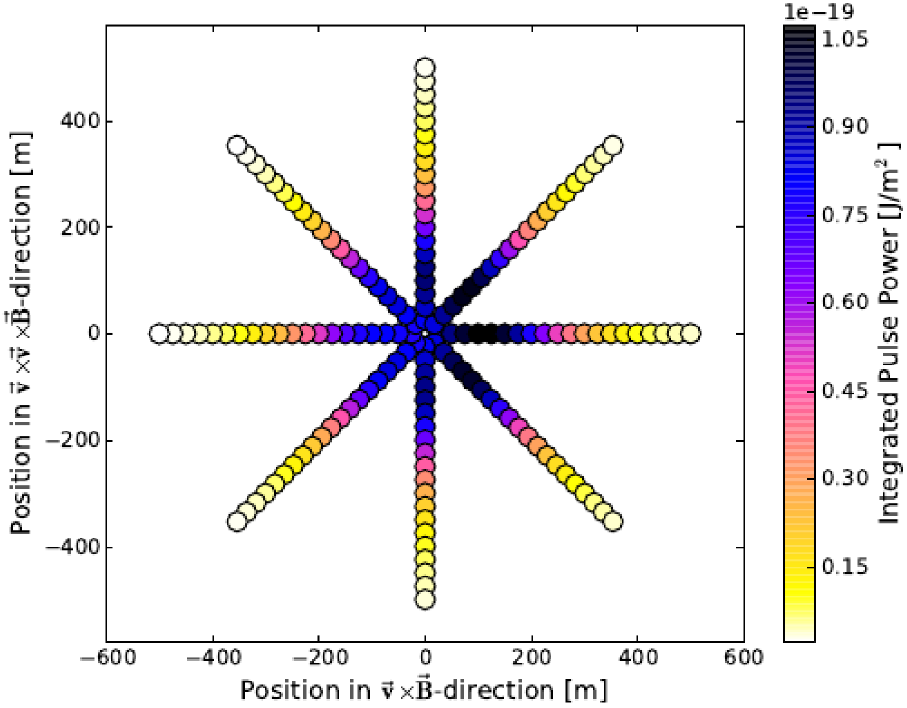
Fit results for a single simulated shower

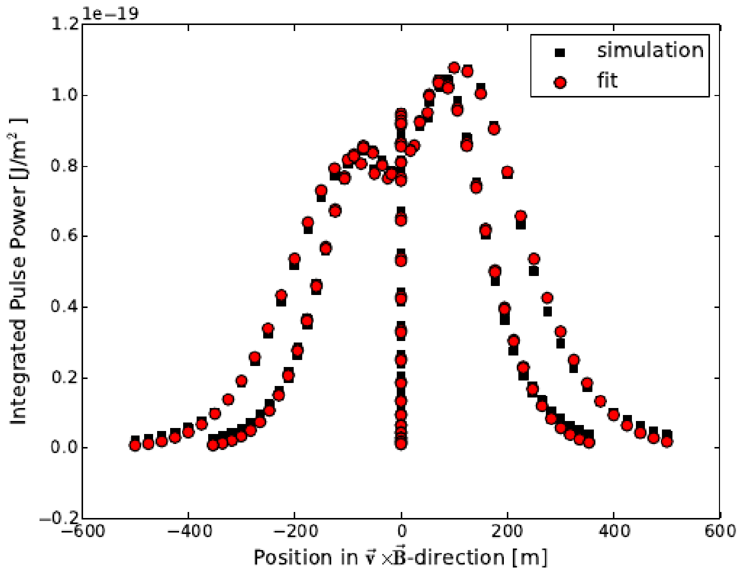


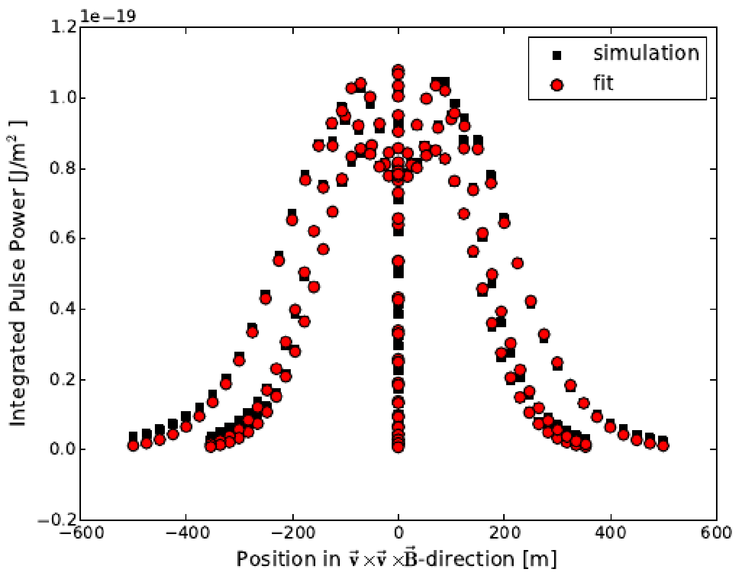


Simulation study

Fit results for a single simulated shower

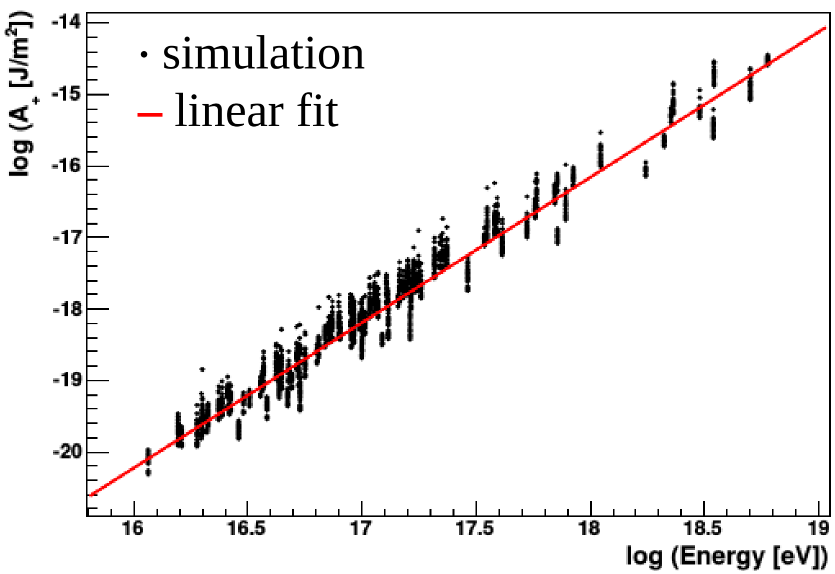


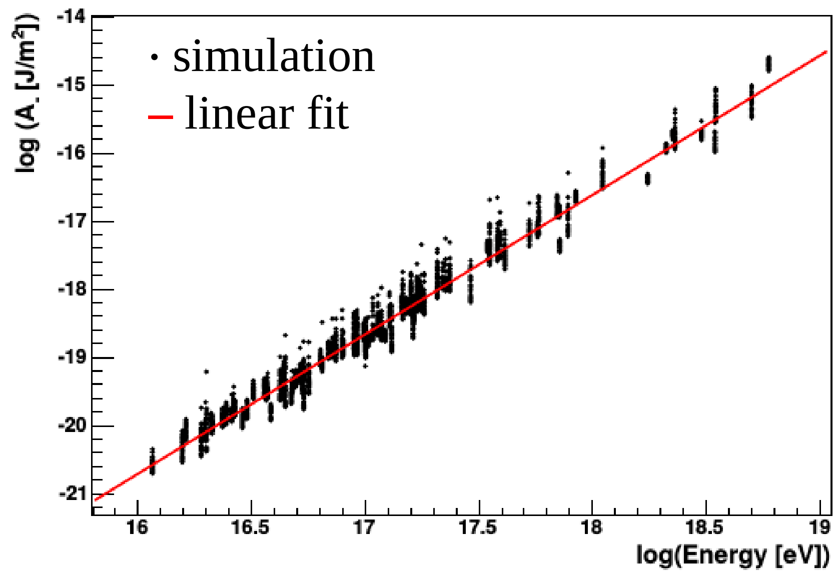




Simulation study

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right)$$



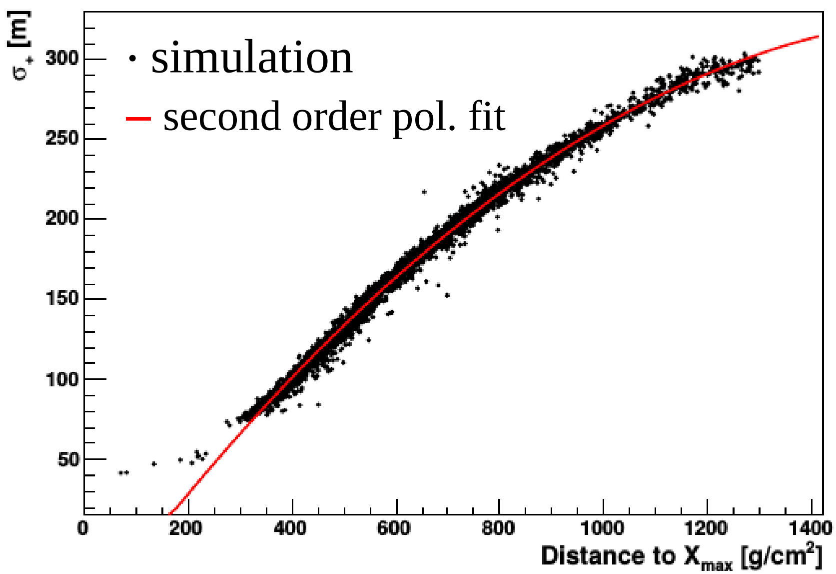


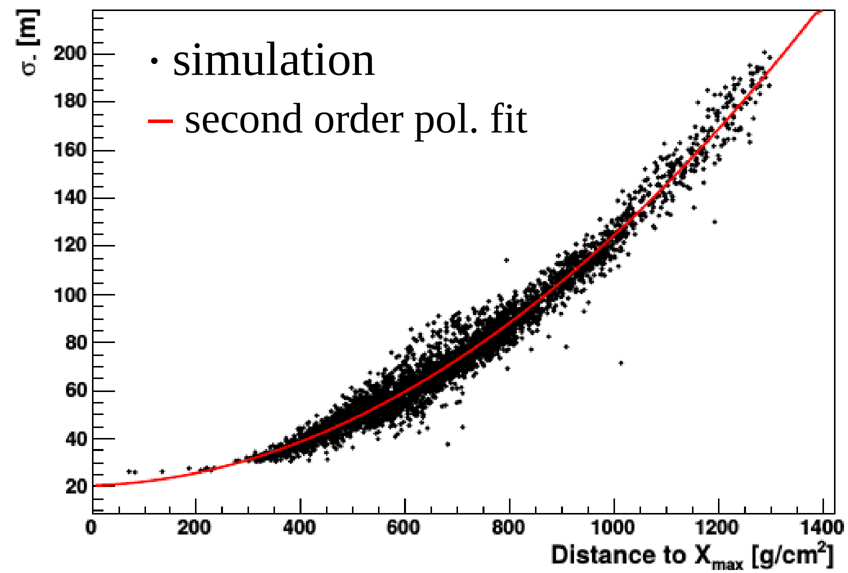
$A_\pm \propto n_{charged} \propto E^2$

For coherent emission

Simulation study

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right)$$



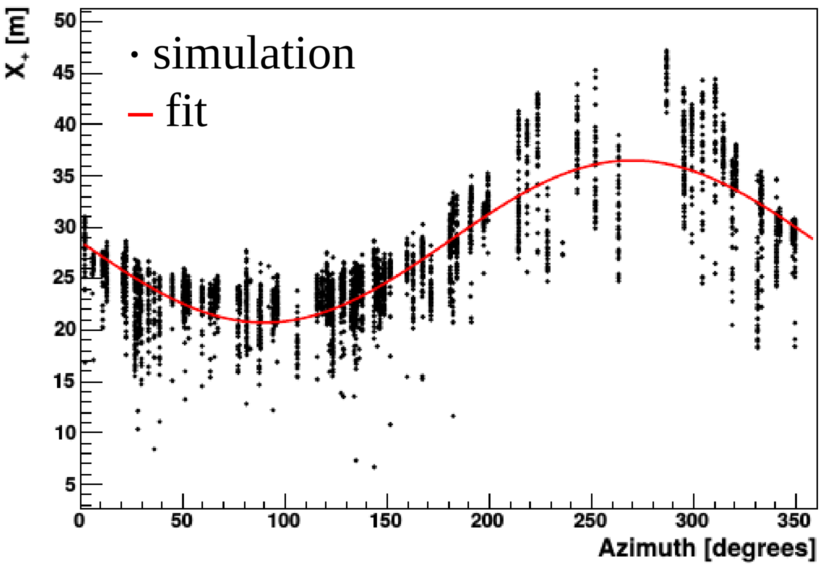


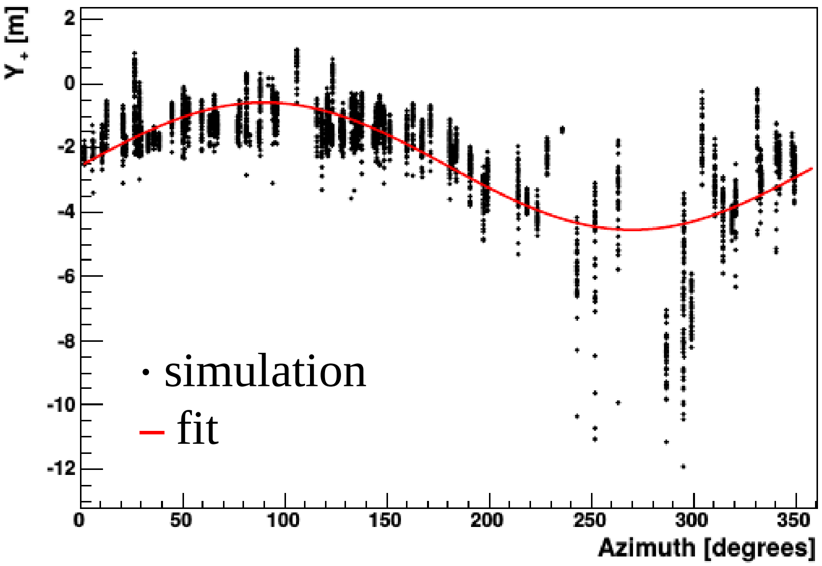
Width of the distribution $\sigma_\pm$ is proportional to the distance of the shower maximum from ground level

$$D(X_{\rm max})[{\rm g/cm^2}] = X_{\rm atm}[{\rm g/cm^2}]/\cos(\theta) - X_{\rm max}[{\rm g/cm^2}]$$

Simulation study

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_+)^2+(y'-Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x'-X_-)^2+(y'-Y_-)^2]}{\sigma_-^2}\right)$$





Shift of the positive and negative Gaussian w.r.t. the shower core is proportional to the azimuth

→ combination of the geomagnetic and charge excess effect in the radio emission

Data analysis: reduction of free parameters

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2+(y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c+x_-))^2+(y'-Y_c)^2]}{(C_3 \cdot e^{C_1+C_2\cdot\sigma_+})^2}\right)$$

The number of free parameters can be reduced by considering correlations between parameters

→ the maximum reduction is obtained by using only 4 free parameters

X_C → location parameter along v x B

Y_C → location parameter along v x (v x B)

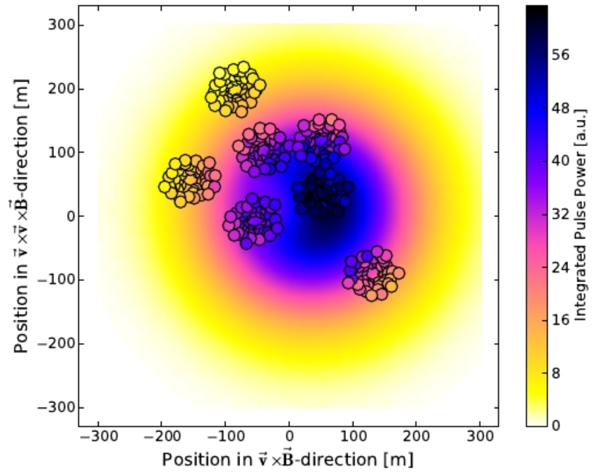
σ_+ → width parameter

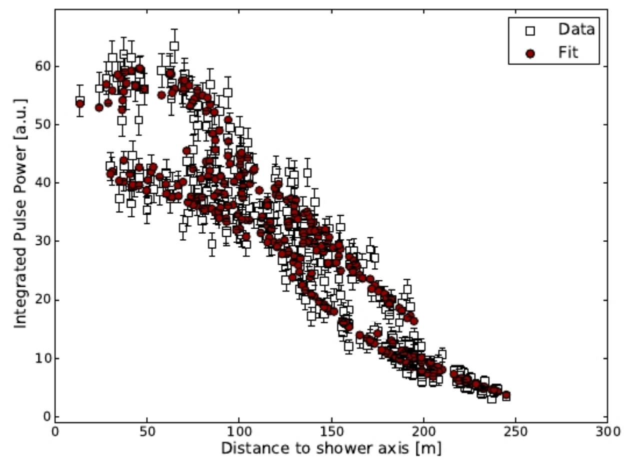
A_+ → amplitude parameter

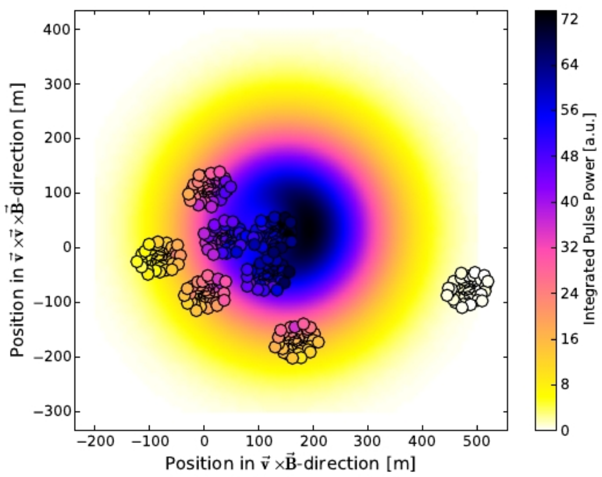
→ C_0 , C_1 and C_2 constant

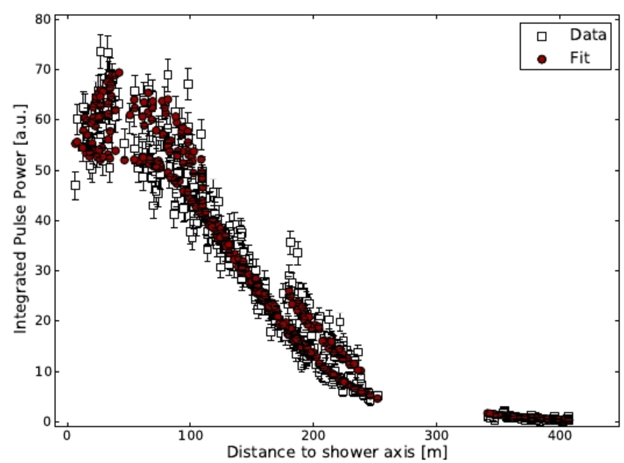
→ C_3 binned for zenith angle

Parametrization applied to DATA



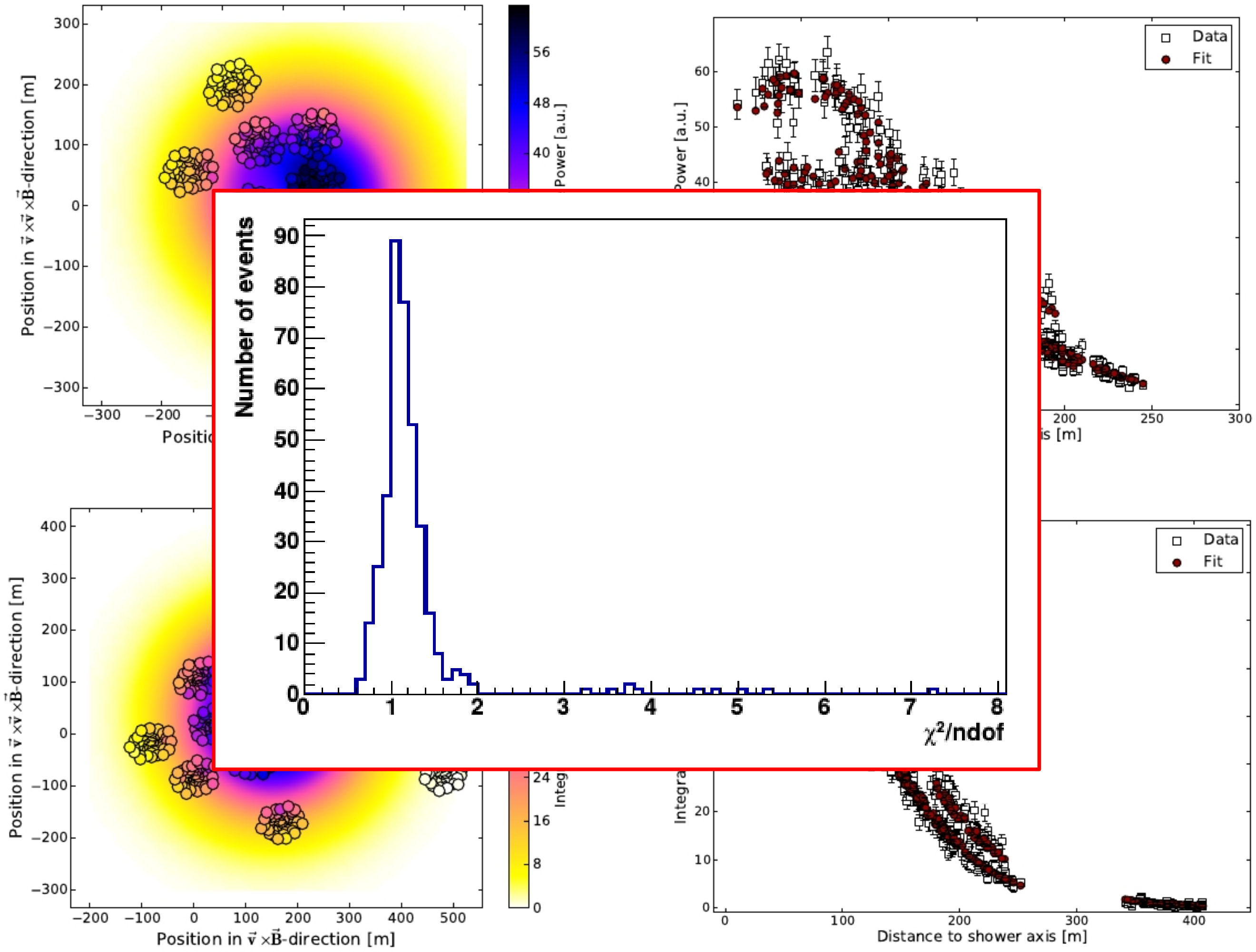






→ Fit applied to ALL LBA LOFAR data

Parametrization applied to DATA



→ Fit applied to ALL LBA LOFAR data

→ Good quality fit

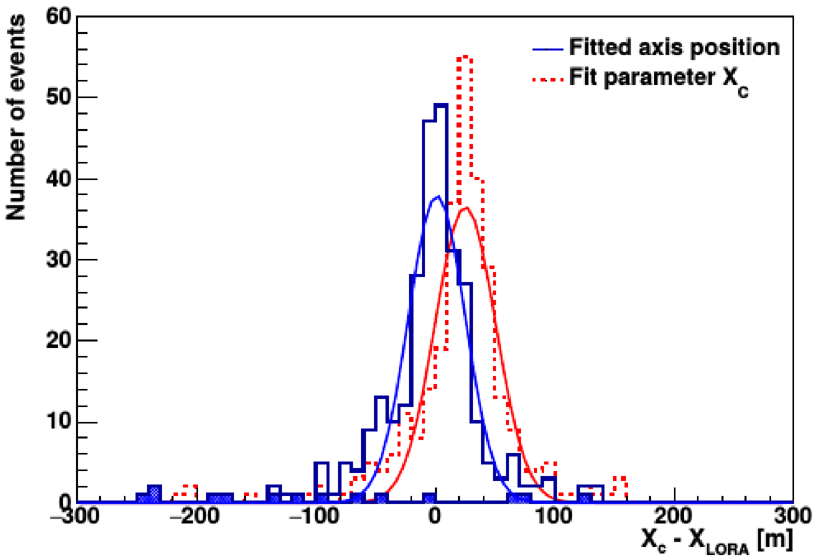
→ events with θ < 15° show slightly less good fit

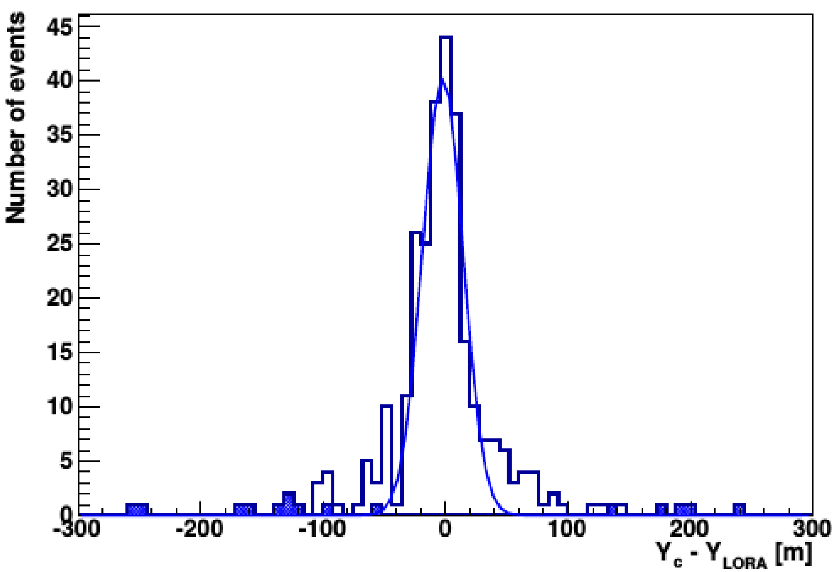
Reconstruction of shower parameters

Shower core position

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2+(y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c+x_-))^2+(y'-Y_c)^2]}{(C_3 \cdot e^{C_1+C_2\cdot\sigma_+})^2}\right)$$

Cross-check with
LORA detectors



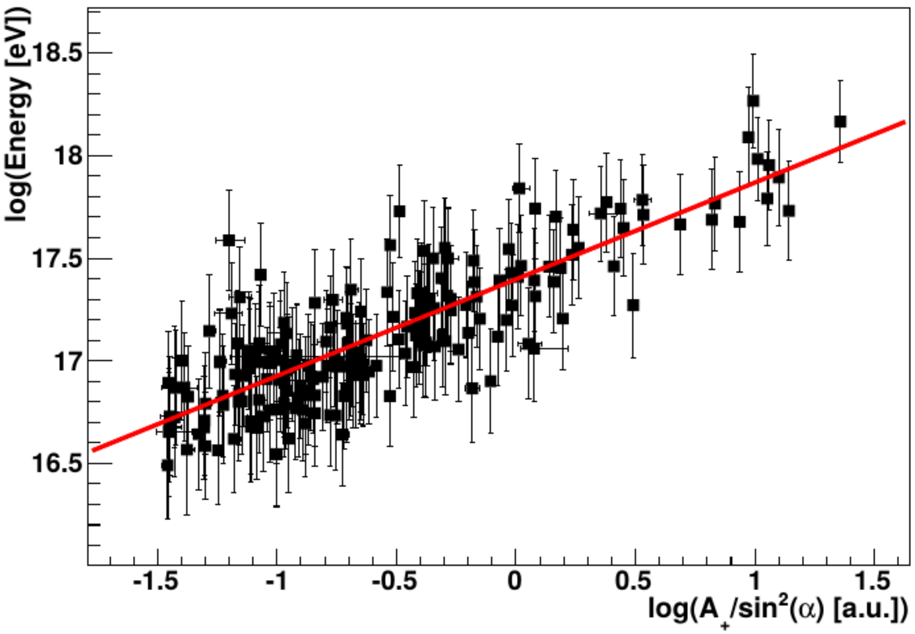


Reconstruction of shower parameters

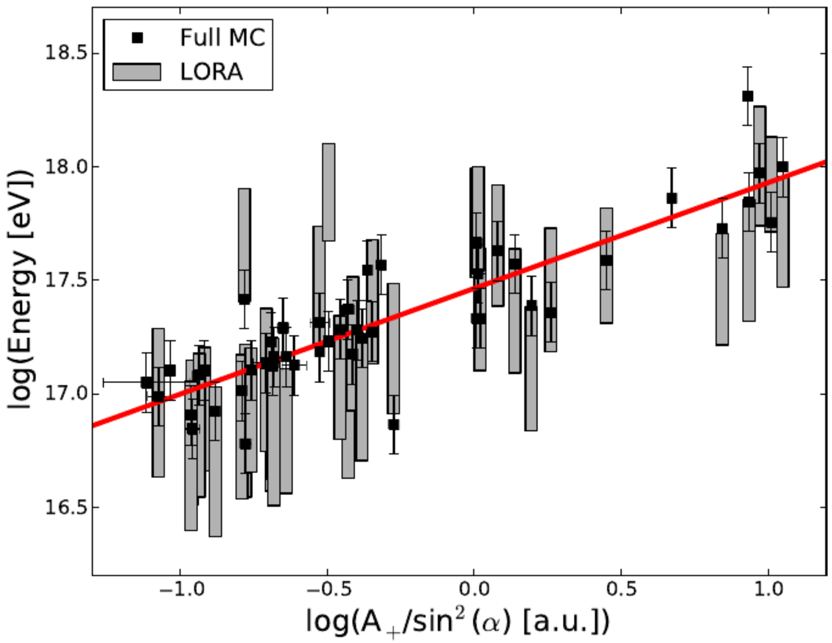
Energy of primary particle

$$P(x',y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2+(y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c+x_-))^2+(y'-Y_c)^2]}{(C_3 \cdot e^{C_1+C_2\cdot\sigma_+})^2}\right)$$

Cross-check with LORA detectors



Cross-check with MC simulations



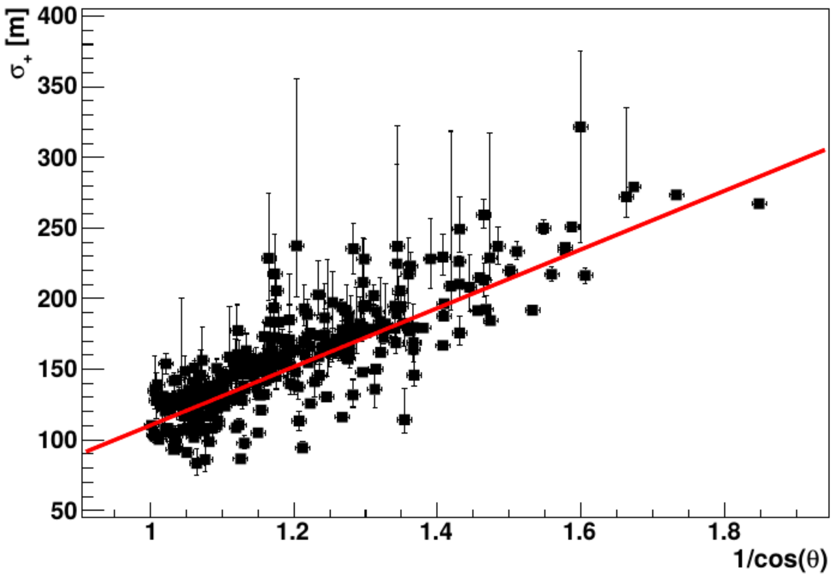
Reconstruction of shower parameters

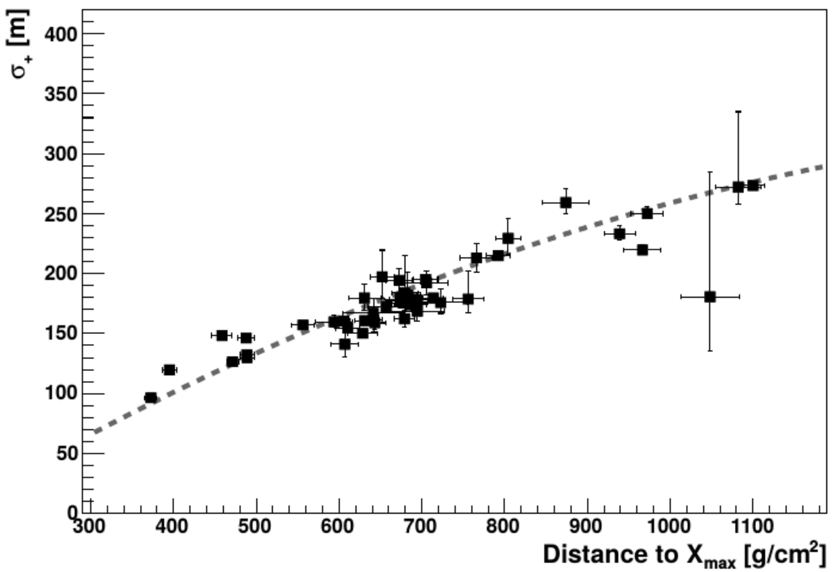
Shower maximum

$$P(x', y') = A_+ \cdot \exp\left(\frac{-[(x'-X_c)^2 + (y'-Y_c)^2]}{\sigma_+^2}\right) - C_0 \cdot A_+ \cdot \exp\left(\frac{-[(x'-(X_c+x_-))^2 + (y'-Y_c)^2]}{(C_3 \cdot e^{C_1 + C_2 \cdot \sigma_+})^2}\right)$$

Width parameter σ_+ proportional to $1/\cos(\theta)$

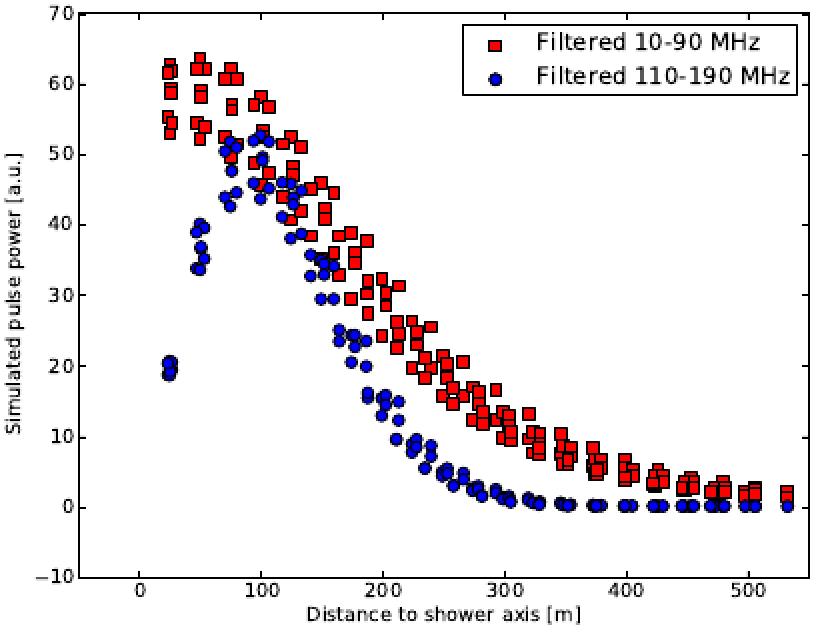
$$D(X_{\max})[\mathrm{g/cm^2}] = X_{\mathrm{atm}}[\mathrm{g/cm^2}]/\cos(\theta) - X_{\max}[\mathrm{g/cm^2}]$$





What does it happen at frequencies around 100 MHz?

A. Nelles et al., 2015, Astroparticle Physics, 65, 11-21

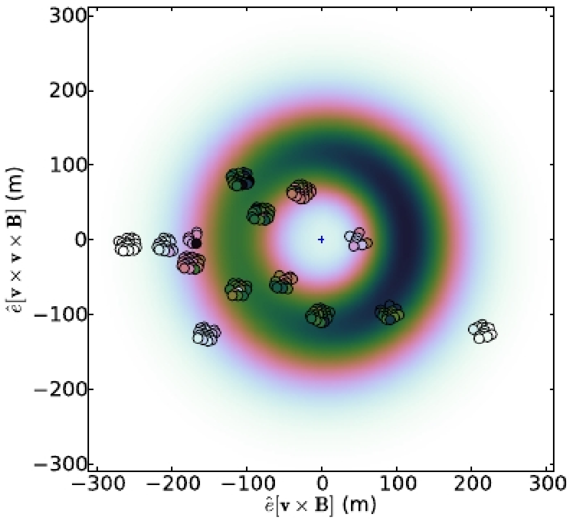


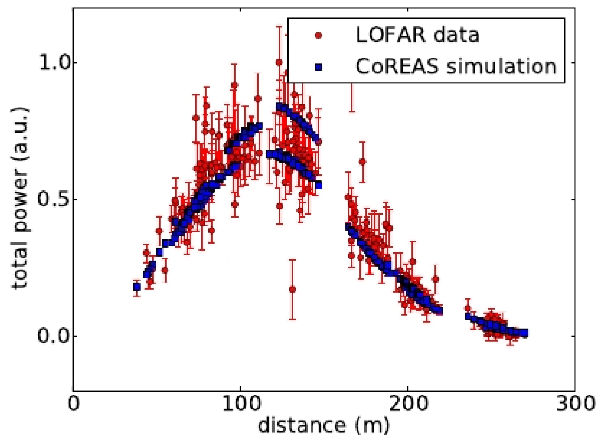
→ Signature of a relativistic time compression

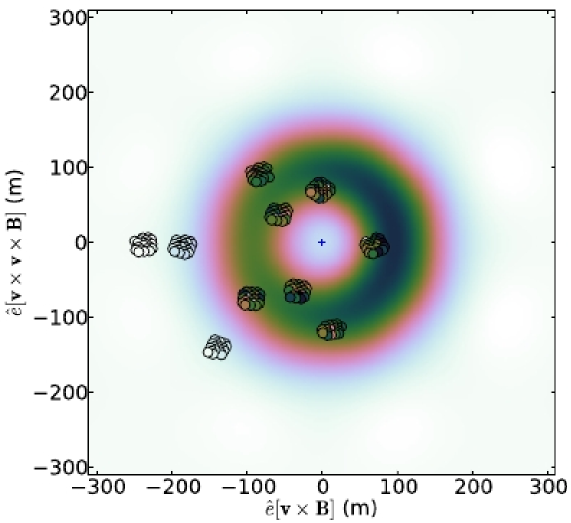
→ the radio emission is amplified at a specific angle w.r.t. the shower axis

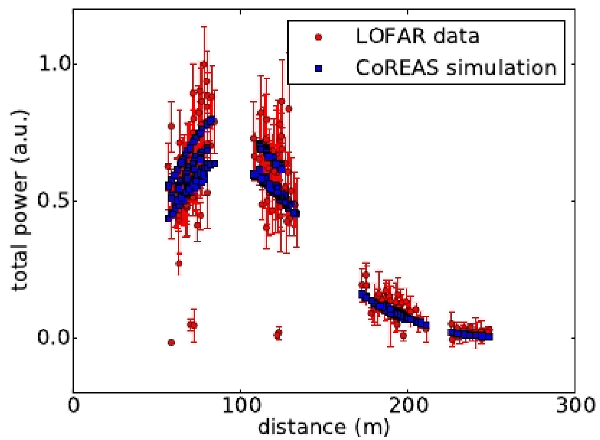
→ “Cherenkov ring” has a diameter of about 100 m and is dominant at frequencies above 100 MHz

Reconstruction of shower parameters









→ Fit applied to HBA data as well

→ amplified ring structure at about 100 m from shower axis

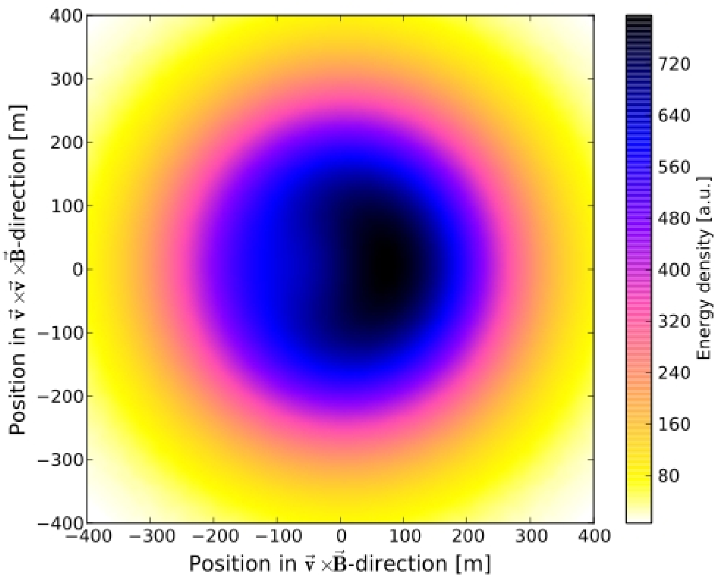
→ ring size sensitive to the depth of the shower maximum

Conclusions

- Simulation study of the radio emission signal at ground level
  → double Gaussian distribution with minimum 4 free parameters
  → parameters related to shower properties

- The parametrization function has been used to fit ALL LOFAR data
  → good agreement for both LBA and HBA data

- Independent method for measuring the energy,
  depth of the shower maximum,
  position of the shower axis at ground level



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